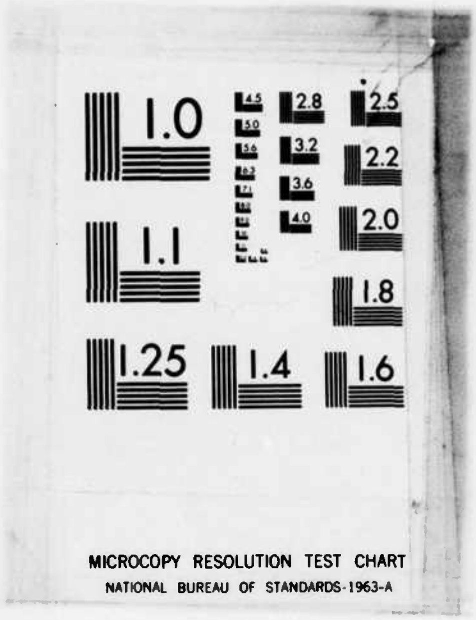
AD-A132 155 A LASER DOPPLER VELOCIMETER FOR MEASUREMENT OF FLOWS INDUCED BY FLAMES PR..(U) PRINCETON UNIV N J DEPT OF AEROSPACE AND MECHANICAL SCIENCES.. R J SANTORO SEP 74 1/1

UNCLASSIFIED PUAMS-1361 F/G 21/2 NL


1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0
4.5
5.0
5.6
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

9

A Laser Doppler Velocimeter for Measurement of Flows Induced by Flames Propagating Over Condensed Fuels

R. J. Santoro

Aerospace and Mechanical Sciences Report #AMS-1361

Sep 1974

PRINCETON UNIVERSITY

Paper File

1

A Laser Doppler Velocimeter for Measurement
of Flows Induced by Flames Propagating
Over Condensed Fuels

R. J. Santoro

Aerospace and Mechanical Sciences Report #PU AMS-1361

Sep. 1974

Guggenheim Laboratories
Department of Aerospace and Mechanical Sciences
Princeton University
Princeton, New Jersey 08540

I. Introduction

The primary process in the spread of fire along the surface of a condensed fuel is heat transfer from the burning region of the fuel to the material ahead of the flame. In the early stages of a fire, the two mechanisms by which this heat transfer occurs are conduction and convection ahead of the flame through the gas and fuel phases. The determination of the importance of the convective heat transfer can be ascertained only by accurate measurement of the fluid flow velocity and temperature fields near the flame front. Convective flows induced by spreading flames are characterized by low fluid velocities with changes in magnitude and direction accompanied by sharp temperature changes occurring over small distances. The bulk gas velocity induced by the flame frequently opposes the propagation. In liquids, there exists, as well, a liquid motion in the direction of the propagation of the flame. These characteristics make quantitative measurements of fluid velocities difficult using conventional techniques. With the advent of Laser Doppler Velocimeter (LDV) techniques, a non-perturbing means of making high resolution measurements of two-dimensional low velocity fields now exists. Thus, the possibility of determining the role of convective effects has become realizable.

After a careful review of possible LDV configurations, a two-component self-aligning design utilizing a Bragg cell was chosen as optimum for the flame spread problem. This system provides the capability for determining two velocity components in flows where flow reversal may occur. Care has been exercised to provide an instrument which is convenient to align and versatile in application.

This report is intended to describe in detail this LDV facility. As such it should prove useful to those who are designing LDV's with similar capabilities or to those who are new to this facility. Some effort has been taken to describe each of the special features of this instrument short of making it a user's manual.

In the next sections a brief introduction to LDV will be presented. This will be followed by the description of the instrument. A section considering optimization and verification studies which have been undertaken will then be given.

II. Laser Doppler Velocimetry

The development of non-intrusive flow diagnostics to measure flow velocity in laminar and turbulent flows has received a great deal of attention over the last fifteen years. Of the numerous techniques considered, laser doppler velocimetry (LDV) has probably received the most attention. This technique essentially relies upon the interaction of a wave phenomena, a moving scatter and a receiver. The receiver detects a wave whose frequency is dependent upon the relative motion of the scatterer and initial wave phenomena.[1,2] Simple elucidation of this phenomenon can be given using the dual scatter geometry in which two laser beams of equal intensity are caused to intersect in space and form a "probe volume" region. Figure 1 shows a schematic visualization of the resulting interference phenomenon. A series of parallel interference fringes result which lie perpendicular to the velocity component to be measured. Now as a particle entrained in the flow traverses the region where the beams cross light is scattered. The particle will scatter more light as it crosses a region of constructive interference (i.e., a bright region) than it scatters in a region of destructive interference (i.e., a dark region). If this scattered light is detected on a photodetector, a signal which oscillates in time will result. The general form of the signal will be that represented in the lower corner of Figure 1. Note that the amplitude of the signal has a guassian-like amplitude envelop due to the fact that the laser beams have guassian intensity distributions.

These signals are referred to as doppler signals because the frequency modulation of the observed signals is due to a frequency shift of the light scattered from the moving particle with respect to the incident light in the frame of reference of the detector. The frequency modulation observed is

directly relatable to the velocity of the entrained scattering particle.[2] This doppler frequency, f_D, is given by

$$f_D = \frac{2v \sin \theta/2}{\lambda}$$

where v is the velocity, θ is the angle between the two crossing beams and λ is the wavelength of the laser light.

It should be noted that in the description given above the interference fringes are stationary in time. This results in a 180° ambiguity in determining the direction of the velocity flow since particles traveling in opposite directions produce identical signals. Such an ambiguity can be undesirable in flow situations where reversal or recirculation regions are present. A technique to resolve this ambiguity involves frequency shifting one of the laser beams with respect to the other.[3,4] When this is accomplished the resulting interference fringes will no longer be stationary but instead will move. To a stationary observer the moving fringes will have a frequency equal to the magnitude of the frequency shift applied to the laser beam. Now as a particle traverses the probe volume the doppler signal will have a frequency higher or lower than the frequency shift dependent on whether the particle is traveling opposite or parallel to the direction of the moving fringes. Thus, the direction of motion of the scattering particle can be ascertained and the directional ambiguity will have been removed.

In actual application frequency shifting can be accomplished in a number of ways including rotating gratings and acousto optic cells. The magnitude of the frequency shift is typically between $10^3 - 10^8$ Hz which is quite small compared to the frequency of light which is about 10^{14} Hz. Thus, frequency shifting does not change the frequency and wavelength of the incident laser

in any appreciable manner but does clearly delineate the directional nature of the flow. In choosing the magnitude of the frequency shift to be applied care must be exercized to assure that the frequency shifting is greater than any possible doppler frequency which can be generated in the direction of the moving fringes. If this condition is not met there still resides an ambiguity for those particles moving parallel to the fringe motion whose resulting unshifted doppler frequency is greater than the shifting frequency.

III. The Laser Doppler Velocimeter Facility

Description of the LDV instrument can be divided into three sections: (1) The LDV Optics, (2) The Processing Electronics, and (3) The Minicomputer Data Acquisition System.

A. The LDV Optics

Figure 2 shows a schematic layout of the optics section of the LDV. The laser light source is a Spectra Physics Model 164 argon ion laser which has a total output power of two watts. The laser is usually tuned to the 5145 Å green line which has a maximum power output of 800 mW. By using a relatively high power light source, fringe contrast within the sample volume is increased and particle seeding requirements are reduced. The output of the laser is continuously variable from about 10 mW to the maximum output of 800 mW for the 5145 Å line. Specific laser power for a particular experiment is chosen to optimize the signal to noise ratio and data rate characteristics.

The output of the laser is passed through a Spectra Physics model 311 3x beam expander to focus the laser beam waist into the two-dimensional ultrasonic Bragg cell. A Newport Research model 670 steering instrument is used to direct the beam into the Bragg cell giving both vertical and azimuthal adjustments of beam direction. Preceding the Bragg cell is an iris type spatial filter which is used to block unwanted reflections and scattered light due to the preceding optical components.

As is depicted in Figure 3 the Bragg cell is used to split the beam into four components and frequency shift the output beams 22.5 MHz and 15 MHz with respect to each other. Frequency shifting of the beams produces moving fringes within the sampling volume, thus resolving directional

ambiguity of the velocity measurements in the vicinity of flow reversal regions. A two-dimensional Bragg cell producing four beams (and two orthogonal sets of moving fringe) is required if a two-dimensional velocity determination is to be made. The Bragg cell and its driving electronics were obtained from Spectron Development Laboratories. Appendix I contains a more detailed explanation of the principles involved in the Bragg cell operation.

After the Bragg cell, the beams are directed through a Spectra Physics model 330 6x beam reducer to increase the divergence between the beams. Such optical processing is required if the proper number of fringes and optimum fringe contrast is to be produced in the probe volume. Before the beams are focused to form the probe volume, the four beams are passed through a simple spatial filter to eliminate scattered light from preceding optical components. The beams are then focused using a simple convex lens to form the probe volume (containing the two sets of orthogonal moving fringes) at the measuring point of interest. The focal length of the lens provides a means of adjusting the fringe spacing (and therefore the doppler period) and thus a number of different lenses are used. Typically a lense with a focal length of 25 cm is used.

Following the probe volume, the original four beams are blocked by optical stops to allow for the detection of scattered radiation from flow entrained particles passing through the probe volume. Before placing the optical stops in the beam path, the collecting optics are adjusted so that the beams are focused on a single photomultiplier (PMT). This approach assures the maximum light collection from the probe volume (thus the origin of the term self-aligning[3]). The collecting optics consists of two 3 inch

diameter lenses whose individual focal length are 30 cm. Large lenses are used to enhance light collection efficiency.

Before entering the PMT, the light passes through a narrow band optical filter centered at 5145 ± 10 Å. This filter provides for rejection of background radiation particularly that which could arise from the flame. The PMT is an RCA 931A which is an inexpensive PMT tube whose sensitivity peaks in the blue region. The high power laser source utilized in this experiment does not require the use of an expensive photodetection system. The PMT is operated at between 700 and 1000 V dc using a Pacific Photometric Instrument model 204 negative high voltage power supply.

The experiment itself is located on a lathe bed which allows accurate positioning of the probe volume with respect to the surface of the material under study. The major advantage of this arrangement is that the LDV components are held rigid thus eliminating alignment problems introduced when the probe volume is moved with respect to the material surface. To aid in the alignment of the instrument, the critical elements such as beam reducers, the Bragg cell, focusing and collecting optics, and the PMT have been mounted on translating bases and/or dual positioning mirror mounts for critical positioning with respect to the beam. The overall effect of these considerations has been to produce an instrument which is relatively easy to align.

B. The Processing Electronics

Figure 4 shows a schematic representation of the electronics used to process the output signal received from the photomultiplier. Following the photomultiplier the signal is input into a Spectron Development Laboratory model DSS-1522 signal separator. This separator provides a number of electronic functions which include pre-amplification, signal filtering and conditioning, electronic heterodyning and noise suppression.

The first stage of the signal separator utilizes a pre-amplifier to remove the dc portion of the signal (commonly referred to as the dc pedestal) and to amplify the signal. The amplification is continuously variable from one to ten. After the pre-amplifier the signal is processed by a narrow bandpass amplifier which separates the 15 MHz and 22.5 MHz carrier signals (plus the doppler shifted frequency residing with each carrier). The separated signals are then electronically heterodyned to remove the carrier frequencies. The unit in addition has the capability of providing a zero offset frequency of between 0 and 900 kHz in steps of 10 kHz. The offset selection determines the doppler frequency shift for an entrained particle with zero velocity. Normally the offset frequency should be chosen such that the largest doppler frequency observable in the flow is less than the offset frequency. This assures that directional ambiguity is removed from the measurement. The signals are then passed through a low pass filter to remove undesirable high frequency ($> 10^6$ Hz) noise. Following this filtering the signals from each channel are output to a burst processor.

It should be pointed out that the oscillator used to provide the 22.5 MHz and 15 MHz signals for the signal separator are also used to drive the Bragg cell. Thus, if the master oscillator should drift slightly the

entire system drifts in an identical manner. Since only difference frequency result at the output of the instrument, differences due to oscillator drift will cancel out.

Burst processors are utilized to determine the period of a signal occurring randomly in time which has some minimum number of cycles. In the present system Spectron Development Laboratory PDAP 501 processors are utilized. These processors have a frequency response range of 100 Hz to 1 MHz. The period measurement is made by comparing the "average" period measured over two differing numbers of cycles. If the comparison differs by more than some pre-set percentage, the measurement is rejected. For example, a period determination for the signal may be made over 5 cycles and compared with that made for 8 cycles, if the measurements differ by more than 10% the measurement is rejected. In this description the average for the smaller number of cycles is termed the "short count" while for the larger number of cycles it is termed the "long count." For these processors the number of cycles chosen for the short and long counts are selectable in a range of 1 to 99. An internal calibration system allows calibration of the instrument to within 1%. A threshold setting on the instrument provides means for choosing a minimum signal level for an LDV signal to be processed. The maximum percent periodicity error is continuously variably from 0.1% to 10%, although settings less than 1% are not recommended. Normally the comparison error is chosen to be 10% for reasons which will be detailed later. In addition, the unit has a feature which allows the rejection of the first "N" cycles of the signal where N varies from 1 to 15. This feature provides a means of rejecting cycles early on in the doppler burst where the signal to noise is poorest.

The processed data is output from each burst processor as two channels of data, a "long count" and a "short count" measurement. These are output in the form of a sixteen bit binary word of which the first twelve bits contain the measurement. Bits 12 and 13 of the long word contain the range information (i.e., the power of ten information). In Appendix II the detail conversion of the binary signal to a frequency measurement is presented.

C. The Data Acquisition System

The data output from the burst processor is transferred to a disc-based minicomputer utilizing a seven channel multiplexer unit. The multiplexer provides a convenient means of inputting several channels of data through a single electronic channel of the computer. This operation is accomplished by reading each of the channels of the multiplexer sequentially under computer control.

The multiplexer utilized in this instrument transfers essentially three types of information to the computer: (1) the period measurements of the doppler signal from the burst processor, (2) a reading from an interval timer to give a time mark to each data point, and (3) a reading giving the status of the experiment.

Turning to the first type of information, four channels of data (each burst processor outputs both the "long" and "short" count measurements) contain the period measurement for the doppler frequency. Each pair of reading from a processor must be within the pre-selected maximum percent periodicity error limits chosen on the processor. Usually this limit is chosen to be 10% to maximize the data rate. If smaller error limits are required, data reduction using the computer after completing the experiment can be done to reduce the data set. Once stored in the computer system the data can be reduced to provide the velocity measurements as detailed in Appendix III.

The time mark information is provided as part of multiplexer circuitry. An interval timer using a 1 MHz crystal oscillator is coupled to a 32 bit counter. Thus two words (since each word contains 16 bits) of data are taken to provide the time mark for the velocity measurement. When an LDV signal is processed the output of the interval time is latched into memory. The interval timer is initiated under control of the experiment and can clock at rates of 100 Hz, 1 kHz, 10 kHz, and 100 kHz as required. Thus the time resolution of the clock can be varied from 10 msec to 10 μsec.

The final channel of the multiplexer is used to provide a status word to the computer. Each of the sixteen bits of this word are capable of being controlled by the external experiment. Presently three of these bits are used in conjunction with microswitches to indicate experiment initiation (and zeroing of the interval timer), flame arrival at the probe volume and experiment terminal. Since the use of these bits are at the disposal of the experimenter, a number of applications for their use could be considered.

Triggering of the multiplexer also has some flexibility. Since there are two velocity components determined in the experiment, the multiplexer has the option of being triggered by either channel or determining simultaneity of the signals. In the simultaneous mode, the signal from the two processes must be due to the same scattering particle thus assuring that the two components are simultaneous measurements.

Following the multiplexer the data is read into a Hewlett-Packard 21 MX minicomputer with 32 K words of memory. Data acquired into memory is then transferred to a disc for permanent storage. The disc system has a storage of 2.5 million words of data. Acquisition and analysis programs have been developed for the LDV facility and are described in Appendix III.

IV. Optimization and Verification Experiments

The LDV facility previously described is a complex instrumental installation where optical and electronic components are linked in an interactive manner to generate, detect, process and convert electronic signals into a velocity determination. The success in obtaining an accurate value for the magnitude of this velocity depends on the control of a number of experimental parameters. These can be divided into two categories: optical and electronic. The optical parameters include:

- Sharpness and spatial resolution of the laser beams to reduce background interference and sharply define the probe volume.
- Alignment of the optical system for accurate focusing of the probe volume onto the photomultiplier tube.
- Selection of the beam crossing angle to achieve the proper number of fringes in the probe volume.
- Achieving a satisfactory ratio between scattered light and background luminosity using proper seeding.

Electronic parameters which must be carefully controlled include:

- Selection of amplification and threshold level for photomultiplier signal in order to optimize signal to noise ratio.
- Reduction of rf and stray light noise sources by careful shielding and alignment.
- Selection of correct amplification levels to drive the Bragg cell in order to produce equal intensity beams emerging from the Bragg cell.

To aid in the optimization of these parameters and at the same time to become familiar with the facility, it was decided to apply the LDV to the

measurement of a well-defined flow. A steady flow field with velocities of the same magnitude as those expected in the fire research experiments was chosen using water as the fluid medium. A square cross-sectional channel 3" x 3" wide and 36" long was used to contain the water. The channel, made of Plexiglas, was provided with inlet flow distributors and flow straighteners so that a uniform flow could be obtained in the early sections of the channel. Water flows from 0 to 200 cm^3/sec were used during the experiment.

With the water flow rate fixed, a systematic variation of the parameters described above was undertaken. This systematic approach permitted optimization of the operation of various optical and electronic components of the LDV. Reduction of rf pickup and proper seeding of the flow had a critical influence on the final performance of the facility.

With the facility in a controlled operative stage, water flow velocity profiles were obtained along a center vertical plane of the channel. An example of the velocity profiles measured in the experiment is shown in Figure 5. The profiles were taken for several flow rates and distances from the flow straighteners. Although the channel was not long enough for the flow to become fully developed, it is interesting to observe the transition in the velocity profiles from a clearly non-developed flow at 40 cm from the flow straighteners to an almost fully-developed flow at 70 cm. Also it is worth noting the capability of the facility to measure velocities as low as 0.2 cm/sec.

Once the operation of the LDV had been verified using a well-defined flow, measurements of the subsurface liquid flow field resulting from flame propagation across the surface of a fuel was undertaken. The ultimate goal of the present research program is to study the role of gas phase effects in flame propagation over solid materials. The approach taken in understanding

the gas phase measurement problem for solids has been to initially study the problem for the liquid fuel case. The liquid studies are thus being used as a diagnostic and familiarization technique for the LDV studies.

A binary mixture of ethonol-water (90 proof) was chosen as the fuel since a comparative data set using a hydrogen bubble technique already existed. All experiments were done with a fuel bulk temperature of 11.5° C. Previous work had identified the dominant energy transfer mode to the region ahead of the flame to be due to a surface tension driven convective flow.

The results of previous work are shown in Figure 6 for comparative purposes. It is clear from the figure that a subsurface convective flow exists which has a recirculation eddy near the flame front. The velocities plotted in Figure 6 are in a reference frame in which the flame front is stationary.

The results of the LDV measurements of the velocity field are shown in Figure 7. Agreement between the two sets of data as to the location of the recirculation eddy and the magnitude and direction of the velocity is very good. It should be pointed out that near the surface of the liquid only the horizontal component of the velocity field could be determined due to a meniscus effect at the edge of the liquid tank. The meniscus prevented focusing the two beams which formed the probe volume for the vertical component. Single component measurements of velocity were made on the surface by focusing the probe volume to intersect the surface from below and thus are actually measurements of the surface velocity. The results of this experiment clearly demonstrated the capability of the LDV to make a two-dimensional velocity measurement in a recirculating flow.

Measurements of the gas phase flow field have also been successfully completed for the ethanol-water case. The results of this study have revealed several interesting features of the induced flow. The treatment of this work will be part of a soon to be completed masters thesis.[5]

Summary

With the completion of the verification and optimization studies, the laser doppler velocimeter facility has become an operational research tool in the fire safety research of the laboratory. The instrument has been shown to be capable of determining flow velocity for both gaseous and liquid media. Experiments have shown the two-component measurements of the velocity can be made in situations where flow reversal is present.

The interfacing of the LDV and the minicomputer data acquisition system has been successfully completed. The ability of this system to meet the data acquisition rates and total storage requirements of the flame spread experiments has been demonstrated.

Acknowledgments

The design and construction of the Laser Doppler Velocimeter facility described in this report has involved the efforts of several of my colleagues. I would like to briefly acknowledge their help here.

During the initial design stages Drs. J. D. Trolinger and W. M. Farmer of Spectron Development Laboratories provided many design suggestions for our facility. A special thanks goes to Dr. J. O. Hornkohl of the Space Institute of the University of Tennessee and Spectron Development Laboratories who designed and built much of the electronics for our system. His interest and cooperation has added greatly to the capability of the final instrument.

I would like to thank Dr. A. Carlos Fernandez-Pello and Mr. Jeffrey Newman who carried out much of the experimental verification and optimization studies as well as the ethanol-water studies. In addition, I would like to acknowledge the efforts of our technicians Mr. Joseph Sivo and Mr. Donald Peoples who fabricated and mounted many of the LDV components.

I would like to especially acknowledge the aid of Professor Irvin Glassman and Dr. Frederick Dryer who had the insight to see the potential of LDV to the fire spread problem as well as the determination to obtain the funding for its construction. Without them there would be no need for this report.

Finally I would like to acknowledge the National Fire Prevention and Control Administration, the National Bureau of Standards, and the Department of Aerospace and Mechanical Sciences for their support in the construction of this facility.

Appendix I. The Bragg Cell

The Bragg diffraction process is a result of the interaction between an acoustical wave and a light wave. The Bragg mode operation requires that

$$n\lambda = 2\ \Lambda\ \sin\phi = 2\Lambda\ \sin\phi$$

where n is the diffraction order, λ is the wavelength of the light beam, Λ is the wavelength of the acoustical wave, and ϕ and θ are the angles of the incident and reflected laser beams with respect to the ultrasonic wavefronts. If we consider the present instrument and take $n = 1$ we can solve for the reflection angle.

$$\theta = \sin^{-1}\ (\lambda/2\Lambda).$$

If we substitute for Λ, v_s/f where v_s is the velocity of sound through water and f is the acoustical driver frequency, we can solve for θ. The velocity of sound through water enters into the analysis since water is the medium utilized in this Bragg cell. If we consider the 22.5 MHz channel and solve for θ we find the reflected angle to be 3.8×10^{-3} rad.

This is a small angle, of course, and to provide sufficient beam separation either long projection distances or a means of increasing the divergence between the beams is required. In the present case a 6x beam reducer is used to increase the divergence.

Adjustment of beam intensity ratio is controlled by the power input into the Bragg cell cyrstals for each channel. The diffraction is varied by positioning adjustments on the Bragg cell mount. With careful adjustment four beams of nearly equal intensity can be produced. Fine adjustment of the beam intensity is accomplished by adjustment of impedance matching filters located on the Bragg cell crystal inputs.

In addition to splitting the incoming beams, the Bragg cell also results in frequency shifting the light beam $\pm f$. This is a result of the diffraction of the light beam by the moving acoustical wave. Beams emerging from the Bragg cell can be represented as f(0,0), f(22.5,0), f(0,15), and f(22.5,15) to represent the relative frequency shift in megahertz. Such frequency shifted beams when recombined to form an interference region produce a moving fringe pattern. This situation allows for the determination of the direction as well as the velocity of entrained particles in the flow.

Thus the Bragg cell can be seen to be a convenient means for producing four equal intensity frequency shifted light beams. The use of a single device to accomplish both required beam attributes also adds an element of simplicity to the design.

Appendix II. Burst Processor Data Conversion

The data output from each of the PDP 501 burst processors is in the form of two sixteen bit binary words. These sixteen bit words contain the measurement of doppler signal period for the short and long count averages. Of these sixteen bits the first twelve bits (bits zero through eleven) contain the binary representation of the doppler period while bits twelve and thirteen of the long count average contain a power of ten multiplicative factor for the data. The doppler period measured in this manner has the units of microseconds.

The conversion of this binary data to a floating point number is accomplished by separating (masking) the first twelve bits from the power of ten range information. Table II-1 shows the conversion of the range bit information to a power of ten format

TABLE II-1

			Range = $10^{(n-2)}$
bit	13	12	n
	ϕ	ϕ	ϕ
	ϕ	1	1
	1	ϕ	2
	1	1	3

The measured period can then be found by converting the first twelve bits to a decimal number, dividing by four and multipling by the range value. The long and short count values for the period can then be averaged for each channel.

Masking of the data word to separate the power of ten multiplicative factor as well as the conversion of the binary representation to a floating point representation is done within a Fortran data analysis program. Using the information given above this conversion and masking becomes a straight forward programming problem. The program presently used in given in Appendix III.

Appendix III. Software for Data Acquisition

As previously described, the burst processor measurements, interval timer information and status word data are input to a disc-based minicomputer for storage. The channels of data recorded consist of two data words from each burst processor, two data words from the timer and one status word, for a total of seven data words. These seven data words are generated for each acceptable LDV signal. A seven channel multiplexer allows all the data words to be read via a single channel (i.e., input/output card) of the computer.

The challenge for the data acquisition system is to acquire and store the data without losing any data due to the time gaps generated by the acquisition process. The process of storing data via a computer must address two important factors:

(1) Can the computer acquire and store data at the rate the experiment generates it?

(2) Is there sufficient memory storage capacity to store all the data generated?

Thus one is faced with a dual problem. Fortunately if a mass storage device is coupled to the computer usually both of these questions can be answered affirmatively. For the present experimental problem the average data rate is less than one thousand reading per second with experiment times of the order of minutes. Thus a storage capacity of at least 60000 words is required. Since this exceeds the capabilities of a minicomputer alone, a disc system with a 2.5 million word capacity has been incorporated in the system.

A data rate of 1000 word/sec is typically not a problem for a minicomputer which can generally handle data rates of up to 10^5 words/sec.

The problem encountered is to transfer data from the memory of the computer to the disc storage system simultaneously with the acquisition of more data. To accomplish this task a double buffering system is used. One buffer is filled with data while a second buffer transfers previously acquired data to the disc. When the first buffer is filled the roles of the two buffers are switched. A buffer in this description refers to a block of contiguous memory locations used to store data, i.e., an array. The condition which must be satisfied in this situation is that the time to read the contents of the second buffer to the disc must be less than the time needed to fill the buffer acquiring data. In general this condition can be met by a proper choice of the buffer sizes.

The Hewlett-Packard operating system fortunately has a system for accomplishing this double buffering scheme as do most computer operating systems. In the Hewlett-Packard system this technique is termed "Class Input/Output." Thus calls to subroutines to accomplish this double buffering can be written in Fortran. The details of Class I/O are given in the Hewlett-Packard RTE (Real Time Encentive) Manual and will not be duplicated here.

In addition to the double buffer technique the computer software must have a means of detecting the start and termination of an experiment. To accomplish this task the status word entry is utilized. Individual bits of this word (there are sixteen bits to a data word) are connected to microswitches (presently three such switches are used). When these switches are opened the appropriate bit in the status changes from logical zero to logical one. By monitering these switches through the status word the status of the experiment can be ascertained. In the present operation the first microswitch is used to indicate the initiation of the experiment and commencement of data acquisition. A second microswitch indicates the arrival of the

flame at the LDV probe volume region and a third microswitch records the termination of the experiment and data acquisition.

The file in which the data is stored is created as a part of this program. Subsequent data analysis programs have been written to convert the doppler period measurements to velocity and convert the timer readings to time in seconds.

Within this program the maximum percent periodicity error window allowed for differences between the long and short averages of the doppler period can be reduced from the ten percent figure mentioned earlier. By operating the processors at a ten percent window the data rate can be maximized while allowing for data accuracy improvement at a later time.

By combining the status word information with the interval time data, flame spread rates can be determined if the distance between the microswitches is accurately known.

Copies of the data acquisition and reduction programs are included in this appendix.

```
FTN,L
      PROGRAM LDV03
C   *THIS PROGRAM ACQUIRES DATA FROM THE LDV BURST PROCESSORS
C   *THROUGH A SEVEN CHANNEL MULTIPLEXER. THE DATA IS THEN STORED
C   *IN A FILE ON THE DISC. THIS FILE IS CREATED WHEN THE PROGRAM
C   *IS RUN. THE FILE TYPE,LENGTH,AND RECORD SIZE ARE SPECIFIED
C   * WITHIN THE PROGRAM. THE DATA IS ACQUIRED USING CLASS I/O
C   *INSTRUCTIONS TO ASSURE THAT DATA IS NOT LOST DURING TRANSFER
C   * TO THE DISC.THE DATA FORMAT IS A SIXTEEN BIT INPUT FOR
C   *EACH CHANNEL.THE FIRST FOUR DATA WORDS ON A READ ARE THE
C   *PERIOD DETERMINATIONS FROM THE BURST PROCESSORS(TWO WORDS
C   *FOR EACH VELOCITY COMPONENT). THE NEXT TWO WORDS ARE THE OUT-
C   *PUT FROM THE INTERVAL TIMER WHICH TIME MARKS EACH DATA POINT.
C   *THE LAST WORD IS A STATUS WORD WHICH INPUTS THE STATUS OF A
C   *SERIES OF MICROSWITCHES WHICH ARE USED TO DETERMINE THE
C   *THE BEGINING AND END OF AN EXPERIMENT.
C   ************************************************************
      DIMENSION INAME(3),IDCB(144),IBFA(128),ISTART(2)
      DIMENSION IBFB(128),IREG(2),IEND(2),ITER(2),IOUT(8)
      DIMENSION ISIZE(2),K1(5)
      EQUIVALENCE (REG,IREG)
      DATA IOUT/2HEN,2HTE,2HR ,2HFI,2HLE,2H N,2HAM,2HE /
      CALL RMPAR(K1)
C   *CALL EXEC TO OUTPUT REQUEST FOR FILE NAME
      LU=K1(1)
      IF(K1(1).EQ.0) LU=1
      CALL EXEC(2,LU+400B,IOUT,8)
C   *BLANK FILE NAME OUT
      DO 5 I=1,3
      INAME(I)=2H
    5 CONTINUE
C   *INPUT FILE NAME
      CALL EXEC(1,LU+400B,INAME,3)
C   *INIALIZE SOME CONSTANTS
      ISIZE(1)=200
      ISIZE(2)=128
      ITYPE=1
      IPRM1=0
      IPRM2=0
      NUM=0
      M=0
      N=0
      MM=0
C  *INPUT CARTRIDGE NUMBER
      WRITE(LU,301)
  301 FORMAT('INPUT CARTRIDGE NUMBER-INTEGER VARIABLE')
      READ(LU,*) ICR
C   *CREAT THE FILE
      CALL CREAT(IDCB,IERR,INAME,ISIZE,ITYPE,0,ICR)
      IF(IERR.LT.0) CALL IER(LU,IERR,1)
C   *OPEN THE FILE
      CALL OPEN(IDCB,IERR,INAME,2B,0,ICR)
      IF(IERR.LT.0) CALL IER(LU,IERR,2)
C   *REWIND FILE TO THE BEGINNING
      CALL RWNDF(IDCB,IERR)
      IF(IERR.LT.0) CALL IER(LU,IERR,3)
```

```
C     *OBTAIN CLASS NUMBER
        ICLAS=0
        CALL EXEC(20,0,IBFA,126,IPRM1,IPRM2,ICLAS)
C    * DO A GET CALL TO CLEAR ABOVE READ
        CALL EXEC(21,ICLAS+20000B,IBFA,126)
C     *CHECK TO SEE IF THE EXPERIMENT HAS STARTED
     15 CALL EXEC(1,12+200B,ISTAT,1)
        A=IAND(000001B,ISTAT)
        IF(A.NE.000001B) GOTO 15
        WRITE(LU,102)
    102 FORMAT('THE FIRST MICROSWITCH HAS TRIPPED')
C     *CLASS I/O READ A
        CALL EXEC(17,12,IBFA,126,IPRM1,IPRM2,ICLAS)
C     *CLASS I/O READ B
        CALL EXEC(17,12,IBFB,126,IPRM1,IPRM2,ICLAS)
C     *CLASS I/O GET A. PROGRAM SUSPENDS UNTIL READ A COMPLETES
      1 REG=EXEC(21,ICLAS,IBFA,126,IRTN1,IRTN2,IRTN3)
C     *SAVE 'A' AND 'B' REGISTER STATUS. 'B' REGISTER IS TRANSMISSION LOG.
        IBFA(127)=IREG(1)
        IBFA(128)=IREG(2)
        IF(C.EQ.000007B) GOTO 27
C     *CLASS I/O READ A AGAIN
        CALL EXEC(17,12,IBFA,126,IPRM1,IPRM2,ICLAS)
        IF(NUM.GT.00) GOTO 25
        ISTART(1)=IBFA(5)
        ISTART(2)=IBFA(6)
C     *ICREMENT RECORD NUMBER
     25 NUM=NUM+1
C     *CHECK MICROSWITCH STATUS
        IF(M.EQ.1) GOTO 26
        B=IAND(000003B,IBFA(126))
        IF(B.NE.000003B) GOTO26
        M=1
        WRITE(LU,103)
    103 FORMAT('SECOND MICROSWITCH HAS TRIPPED')
     26 C=IAND(000007B,IBFA(126))
        IF(C.NE.000007B) GOTO 27
        IEND(1)=IBFA(124)
        IEND(2)=IBFA(125)
        WRITE(LU,104)
    104 FORMAT('THIRD MICROSWITCH HAS TRIPPED')
        MM=1
C     *WRITE DATA TO THE FILE
     27 CALL WRITF(IDCB,IERR,IBFA,128,NUM)
        IF(IERR.LT.0) CALL IER(LU,IERR,4)
C     *CLASS I/O GET B. PROGRAM SUSPENDS UNTIL READ B COMPLETES.
        REG=EXEC(21,ICLAS,IBFB,126,IRTN1,IRTN2,IRTN3)
C     *SAVE 'A' AND 'B' REGISTERS. 'B' REGISTER HAS TRANSMISSION LOG.
        IBFB(127)=IREG(1)
        IBFB(128)=IREG(2)
        IF(C.EQ.000007B) GOTO 40
C     *CLASS I/O READ B AGAIN.
        CALL EXEC(17,12,IBFB,126,IRPRM1,IPRM2,ICLAS)
C     *INCREMENT RECORD NUMBER
        NUM=NUM+1
C     *CHECK MICROSWITCH STATUS
```

```
      IF(M.EQ.1) GOTO 31
      B=IAND(000003B,IBFB(126))
      IF(B.NE.000003B) GOTO 31
      M=1
      WRITE(LU,103)
   31 IF(MM.EQ.1) GOTO 32
      C=IAND(000007B,IBFB(126))
      IF(C.NE.000007B) GOTO 32
      IEND(1)=IBFB(124)
      IEND(2)=IBFB(125)
      WRITE(LU,104)
C    *WRITE DATA TO THE FILE
   32 CALL WRITF(IDCB,IERR,IBFB,128,NUM)
      IF(IERR.LT.0) CALL IER(LU,IERR,5)
      GOTO 1
C    *WRITE LAST RECORD
   40 CALL WRITF(IDCB,IERR,IBFB,128,NUM)
      IF(IERR.LT.0) CALL IER(LU,IERR,6)
C    *CLOSE FILE
      ITRUN=ISIZE(1)-NUM
      IF(ITRUN.LT.0) ITRUN=0
      CALL CLOSE(IDCB,IERR,ITRUN)
      IF(IERR.LT.0) CALL IER(LU,IERR,7)
C    *OUTPUT NUMBER OF RECORDS WRITTEN
      WRITE(LU,105) NUM
  105 FORMAT('NUMBER OF RECORDS WRITTEN=',I6)
C   *OUTPUT THE STARTING AND ENDING TIME
      WRITE(LU,106) ISTART(1),ISTART(2),IEND(1),IEND(2)
  106 FORMAT('ISTART(1)=',I6,'ISTART(2)=',I6,/
     1'IEND(1)=',I6,'IEND(2)=',I6)
      ITER(1)=IEND(1)-ISTART(1)
      ITER(2)=IEND(2)-ISTART(2)
      TM=FLOAT(ITER(1))
      TM=TM/1000
      WRITE(LU,107) TM
  107 FORMAT('EXPERIMENT DURATION=',F8.4,'SEC')
      STOP
      END

**  NO ERRORS**    PROGRAM = 01352      COMMON = 00000
```

```
C
C
      SUBROUTINE IER(LU,IERR,IVAL)
      WRITE(LU,140) IVAL,IERR
  140 FORMAT('ON CALL NO.',I2,'ERROR',I3,'EXISTS')
      RETURN
      END
```

** NO ERRORS** PROGRAM = 00041 COMMON = 00000

```
FTN4,L
      PROGRAM DATA
C   * THIS PROGRAM CONVERTS LDV DATA FROM A MEASUREMENT OF
C   * THE LDV SIGNAL PERIOD TO A VELOCITY.
      DIMENSION IDCB(144),JDCB(272),IBUF1(128),IDATA(7)
      DIMENSION RBUF1(5),RBUF2(90),IBUF2(180),NAME(3)
      DIMENSION NUNAME(3),ISIZE(2),P(5),THETA(2),II(5)
      REAL LAMDA
      EQUIVALENCE(RBUF2,IBUF2)
      CALL RMPAR(II)
      LU=II(1)
      IF(II(1).EQ.0) LU=1
C   * REQUEST THE FILE NAME WHERE THE LDV DATA IS STORED
      WRITE(LU,101)
  101 FORMAT('INPUT FILE NAME')
C   * INPUT FILE NAME
      CALL EXEC(1,LU+400B,NAME,3)
C   * REQUEST CARTRIDGE NUMBER WHERE FILE IS LOCATED
      WRITE(LU,301)
  301 FORMAT('INPUT CARTRIDGE NUMBER - INTEGER VARIABLE')
      READ(LU,*) ICR
C   * REQUEST LAST RECORD NUMBER
      WRITE(LU,102)
  102 FORMAT('INPUT LAST RECORD NUMBER')
      READ(LU,*) NUMMAX
      WRITE(LU,104)
  104 FORMAT('INPUT FULL LDV ANGLE (RAD) FOR 15 MHZ CHANNEL')
      READ(LU,*) THETA(1)
      THETA(2)=THETA(1)*22.5/15.
C   * INPUT OFFSET FREQUENCY IN HZ
      WRITE(LU,110)
  110 FORMAT('INPUT OFFSET FREQUENCY IN HZ')
      READ(LU,*) OFFSET
C   * INITIALIZE SOME VARIABLES
      LAMDA=5.145E-5
      NUM=0
      ISIZE(1)=NUMMAX
      ISIZE(2)=180
      TINCR=0
C   * OPEN THE FILE
      CALL OPEN(IDCB,IERR,NAME,0)
      IF(IERR.LT.0) CALL IER(LU,IERR,1)
C   * REQUEST NEW FILE NAME
      WRITE(LU,103)
  103 FORMAT('INPUT NAME OF NEW FILE')
      CALL EXEC(1,LU+400B,NUNAME,3)
      CALL CREAT(JDCB,IERR,NUNAME,ISIZE,3,0,ICR)
      IF(IERR.LT.0) CALL IER(LU,IERR,2)
      CALL RWNDF(IDCB,IERR)
      IF(IERR.LT.0)  CALL IER(LU,IERR,3)
      CALL RWNDF(JDCB,IERR)
      IF(IERR.LT.0) CALL IER(LU,IERR,4)
    1 NUM=NUM+1
      CALL READF(IDCB,IERR,IBUF1,128,LEN,NUM)
      IF(IERR.LT.0) CALL IER(LU,IERR,5)
      DO 10 I=1,18
```

```
      DO 20 J=1,7
      IDATA(J)=IBUF1((I-1)*7+J)
   20 CONTINUE
      IPOWR1=IAND(IDATA(1),70000B)
      IPOWR2=IAND(IDATA(3),70000B)
      N=0
      DO 26 K=1,4
      IF(IPOWR1.EQ.N) P(1)=FLOAT(K-1)
      IF(IPOWR2.EQ.N) P(3)=FLOAT(K-1)
      N=N+010000B
   26 CONTINUE
      P(2)=P(1)
      P(4)=P(3)
      IDATA(1)=IAND(IDATA(1),007777B)
      IDATA(3)=IAND(IDATA(3),007777B)
      ICYCLE=IAND(IDATA(5),100000B)
      IF(ICYCLE.EQ.100000B) TINCR=32768.
      IDATA(5)=IAND(IDATA(5),077777B)
      IDATA(7)=IAND(IDATA(7),7B)
      DO 30 L=1,4
      P=P(L)-8
      RBUF1(L)=FLOAT(IDATA(L)/4)*(10.**P)
   30 CONTINUE
      DO 40 M=1,3,2
C     * CHECK TO SEE IF READINGS ARE WITHIN ERROR LIMITS
      DIFF=ABS(RBUF1(M)-RBUF1(M+1))/RBUF1(M)
      IF(DIFF.GT.0.1) RBUF1(M)=0.
      IF(DIFF.GT.0.1) RBUF1(M+1)=0
      IF(M.EQ.1) ANGLE=THETA(1)/2
      IF(M.EQ.3) ANGLE=THETA(2)/2
      COFST=1.-(RBUF1(M)+RBUF1(M+1))*OFFSET/2.
      AVG=LAMDA/(((RBUF1(M)+RBUF1(M+1)))*SIN(ANGLE))*COFST
      IF(M.EQ.1)RBUF1(1)=AVG
      IF(M.EQ.3) RBUF1(2)=AVG
   40 CONTINUE
      RBUF1(3)=(IDATA(5)+TINCR)/1000
      RBUF1(4)=IDATA(6)
      RBUF1(5)=IDATA(7)
      DO 50 N1=1,5
      I1=(I-1)*5
      RBUF2(I1+N1)=RBUF1(N1)
   50 CONTINUE
   10 CONTINUE
      CALL WRITF(JDCB,IERR,IBUF2,180,NUM)
      IF(IERR.LT.0) CALL IER(LU,IERR,6)
      IF((NUM-NUMMAX).EQ.0) GOTO 2
      GOTO 1
    2 CALL CLOSE(IDCB,IERR)
      IF(IERR.LT.0) CALL IER(LU,IERR,7)
      CALL CLOSE(JDCB,IERR)
      IF(IERR.LT.0) CALL IER(LU,IERR,8)
      STOP
      END

**  NO ERRORS**    PROGRAM = 01774       COMMON = 00000
```

```
C
C
      SUBROUTINE IER(LU,IERR,IVAL)
      WRITE(LU,201)IERR,IVAL
  201 FORMAT('ERROR NO.',I3,'EXISTS ON CALL NO.',I3)
      RETURN
      END
```

** NO ERRORS** PROGRAM = 00042 COMMON = 00000

```
FTN4,L
      PROGRAM READ3
      DIMENSION NAME(3), IDCB(272), IBUF1(180), RBUF1(90), I(5)
      EQUIVALENCE(RBUF1,IBUF1)
C     RMPAR GETS LU AND LISTS PARAMETERS
      CALL RMPAR(I)
      IOPTN=0
      ISECU=0
      LU=I(1)
      LIST=I(2)
      IF(I(1).EQ.0) LU=1
      IF(I(2).EQ.0) LIST=6
C     REQUEST FILE NAME TO BE READ
      WRITE(LU,101)
  101 FORMAT("INPUT NAME OF FILE TO BE READ")
C     INPUT FILE NAME
      CALL EXEC(1,LU+400B,NAME,3)
C     REQUEST CARTRIDGE NUMBER WHERE FILE IS LOCATED
      WRITE(LU,401)
  401 FORMAT("INPUT CARTRIDGE NUMBER-INTEGER VARIABLE")
      READ(LU,*) ICR
C     REQUEST FIRST RECORD TO BE READ
      WRITE(LU,102)
  102 FORMAT("INPUT FIRST RECORD TO BE READ")
      READ(LU,*) NUMMIN
C     REQUEST LAST RECORD TO BE READ
      WRITE(LU,103)
  103 FORMAT("INPUT LAST RECORD TO BE READ")
      READ(LU,*) NUMMAX
      CALL OPEN(IDCB,IERR,NAME,IOPTN,ISECU,ICR,256)
      IF(IERR.LT.0) CALL IER(LU,IERR,1)
      CALL RWNDF(IDCB,IERR)
      IF(IERR.LT.0) CALL IER(LU,IERR,2)
      DO 10 K=NUMMIN,NUMMAX
      CALL POSNT(IDCB,IERR,K,1)
      CALL READF(IDCB,IERR,IBUF1,180,LEN)
      WRITE(LIST,9) K
    9 FORMAT(I4)

      IF(IERR.LT.0) CALL IER(LU,IERR,3)

      WRITE(LIST,104) (RBUF1(J), J=1,90)
  104 FORMAT(18(3(F8.3,2X),F2.0,2X,F2.0/))
   10 CONTINUE
      CALL CLOSE(IDCB,IERR)
      IF(IERR.LT.0) CALL IER(LU,IERR,4)
      STOP
      END

**  NO ERRORS**    PROGRAM = 00796      COMMON = 00000
```

Appendix IV. Detail Inventory of Equipment

Supplier	Item	No. of Items
Rolyn Optics Co.	Lenses	2
A. Jaegers	Lenses	1
A. Jaegers	Lenses	1
A. Jaegers	Lenses	1
A. Jaegers	Lenses	1
Newport Research Corp.	Translating Stages	2
Newport Research Corp.	Translating Stages	2
Newport Research Corp.	Translating Corp.	2
Newport Research Corp.	Mirror	1
Newport Research Corp.	Mirror Mount	1
Morrison Steel & Aluminum	Aluminum Sheet	1
Infrared Industries	Laser Filter	1
Newport Research Corp.	Mirror Mount	2
Newport Research Corp.	Mirrors	2
Spectra Physics	Laser	1
Spectron Development Labs Labs.	Bragg Cell	1
Spectron Development Labs.	Bragg Cell Electronics	1
Spectron Development Labs.	Spectrum Translator	1
Spectron Development Labs.	Burst Processor	2
Tektronix, Inc.	Storage Scope	1
Tektronix, Inc.	Dual Time Base	1
Tektonix, Inc.	Dual Trace Amplifier	1
Tektronix, Inc.	Scopecart	1
Tektronix, Inc.	10 x Probes	2
Tektronix, Inc.	Camera	1
Coherent Radiation	Laser Collimator	1
Pacific Photometric	High Voltage Supply	1
Edmunds Scientific	Iris Diaphram	1
Edmunds Scientific	Iris Diaphram	1
American Optical	Laser Safety Glasses	3
Newport Research Corp.	Beam Director	1

References

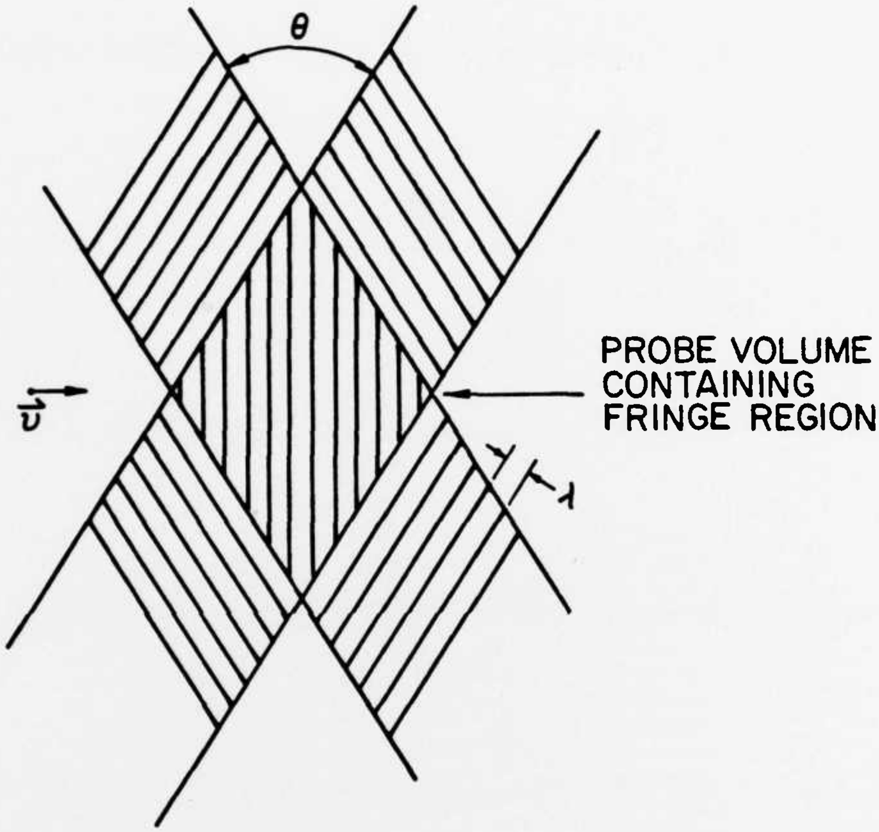
1. Yeh, Y. and Cummins, H. Z., "Localized Fluid Flow Measurements with an He-Ne Laser Spectrometer," Appl. Phys. Lett., 4, 176 (1968).

2. Trolinger, J. D., "Laser Instrumentation for Flow Field Diagnostics," AGARDograph No. 186, Advisory Group for Aerospace Research and Development, NATO.

3. Farmer, W. M. and Hornkohl, J. O., "Two Component Self-Aligning Laser Vector Velocimeter," Appl. Optics, 12, 2636 (1973).

4. Crosswry, F. L. and Hornkohl, J. O., " Signal Conditioning Electronics for a Laser Vector Velocimeter," Rev. Sci. Instrum., 44, 1324 (1973).

5. Newman, J. S., "Laser Doppler Measurements of the Gas and Liquid Flow Fields Induced by Flame Propagation Over a Liquid Fuel Surface," Master Thesis, Department of Aerospace and Mechanical Sciences, Princeton University, Princeton, New Jersey (to be submitted).



$$f_D = \frac{2\upsilon \sin\frac{\theta}{2}}{\lambda}$$

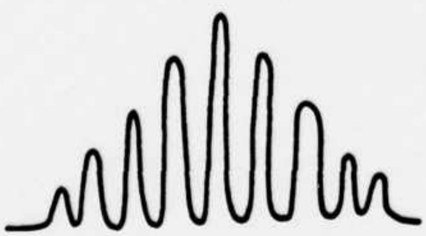
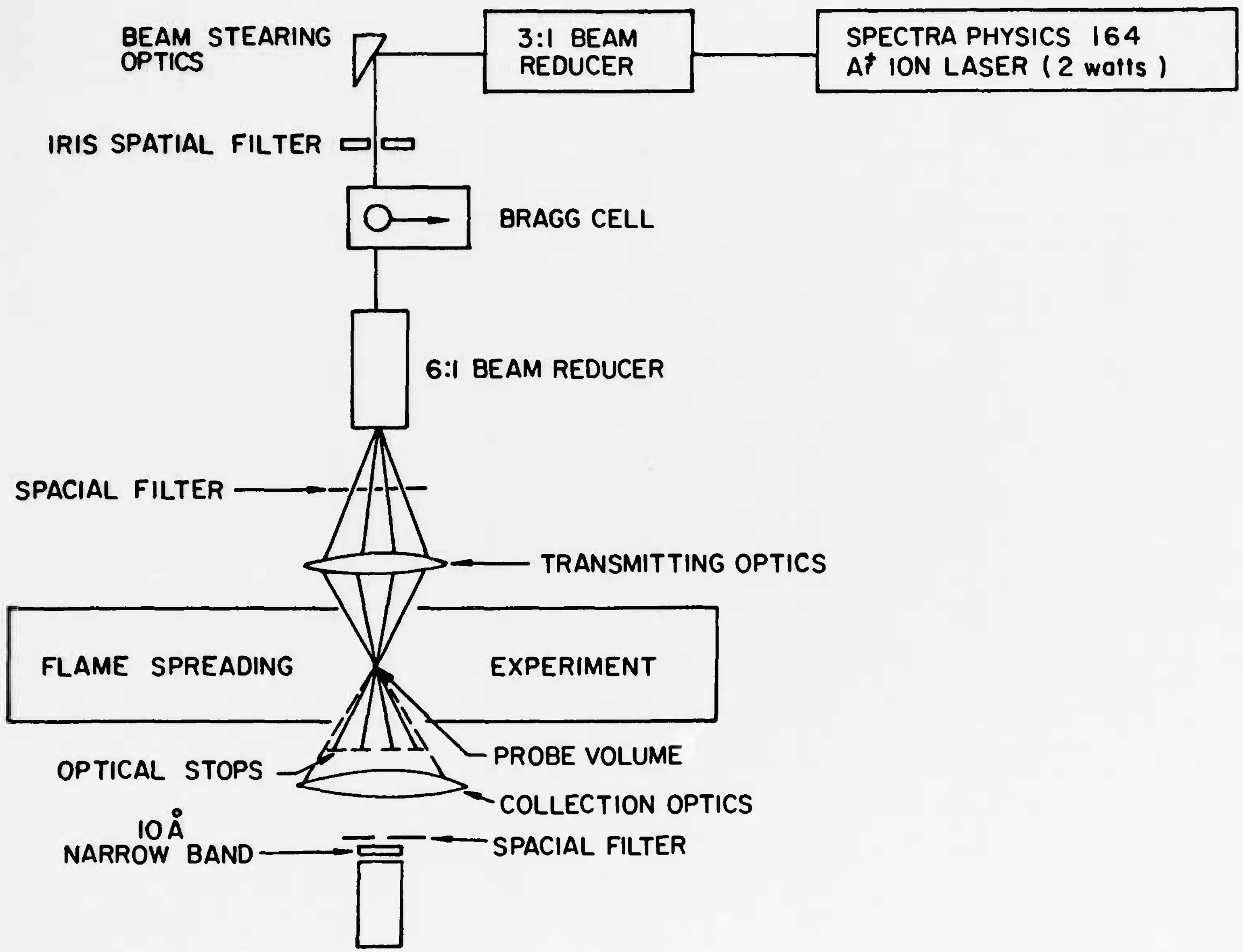


FIGURE 1



LDV OPTICAL SCHEMATIC

FIGURE 2

Two Dimensional Ultrasonic Bragg Cell

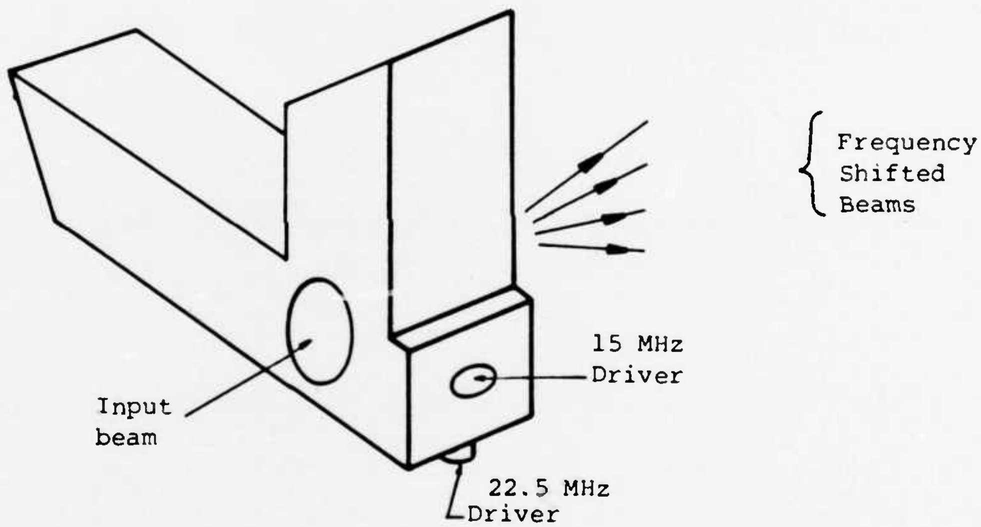
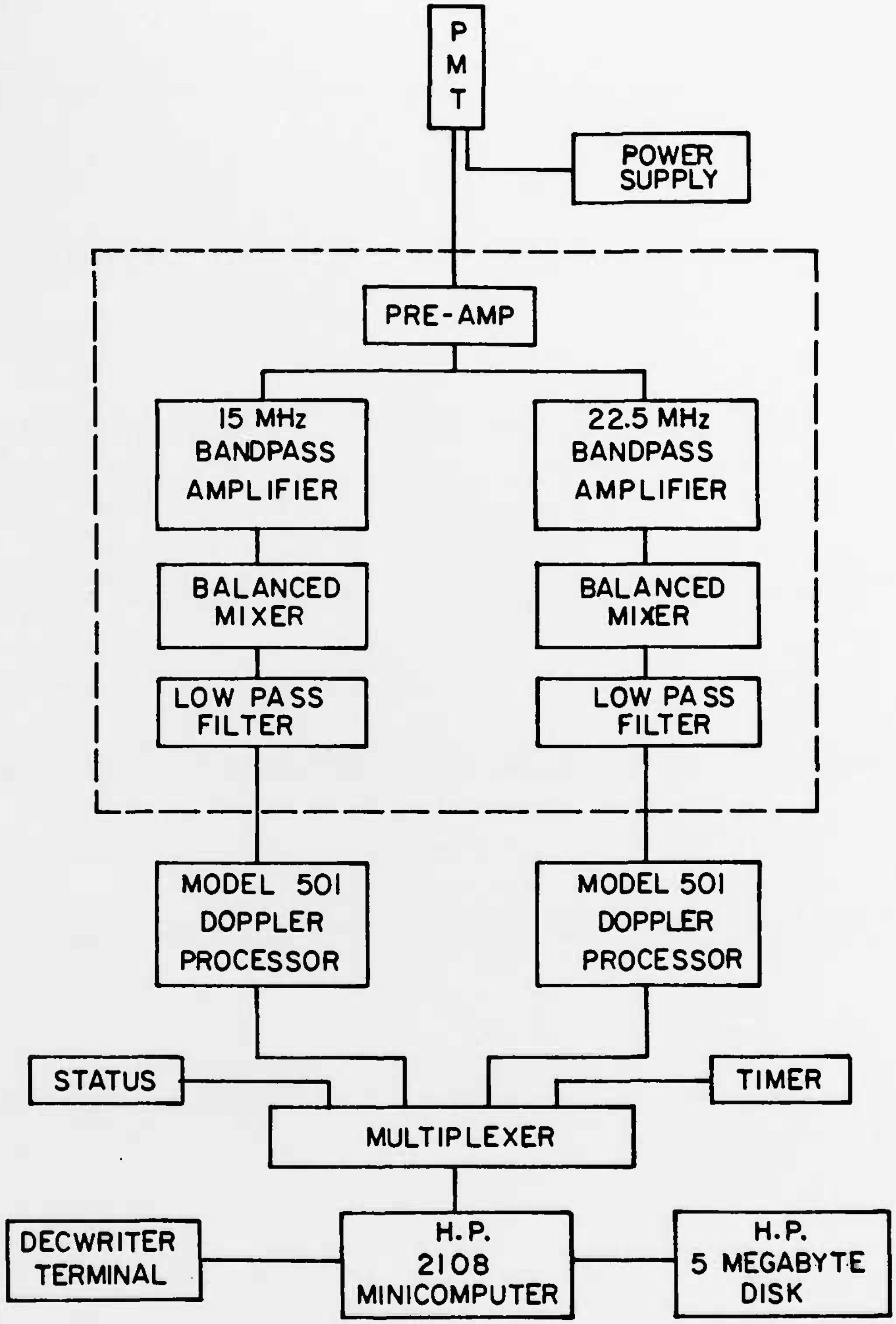
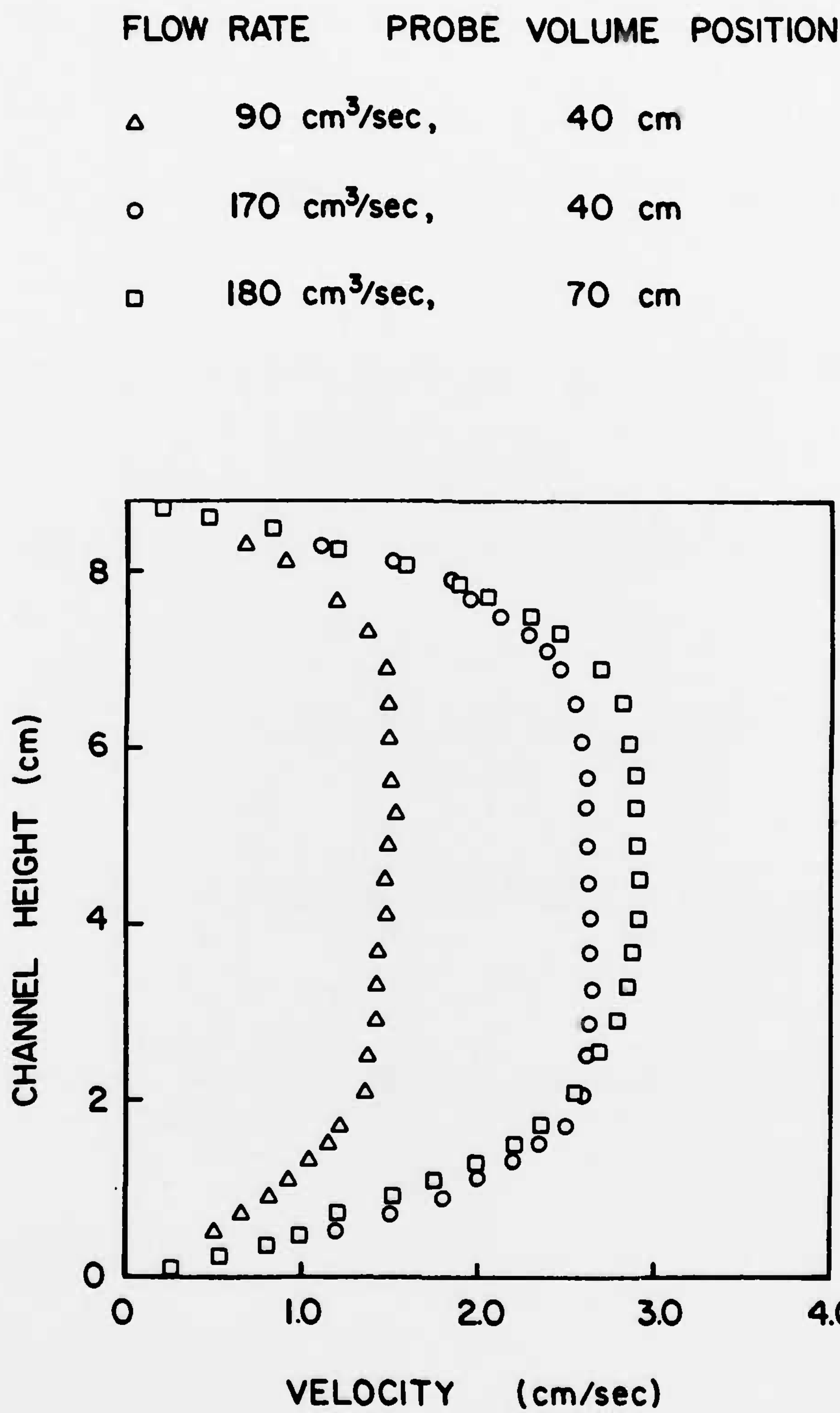


FIG. 3



LDV SIGNAL PROCESSING ELECTRONICS AND DATA ACQUISITION SYSTEM

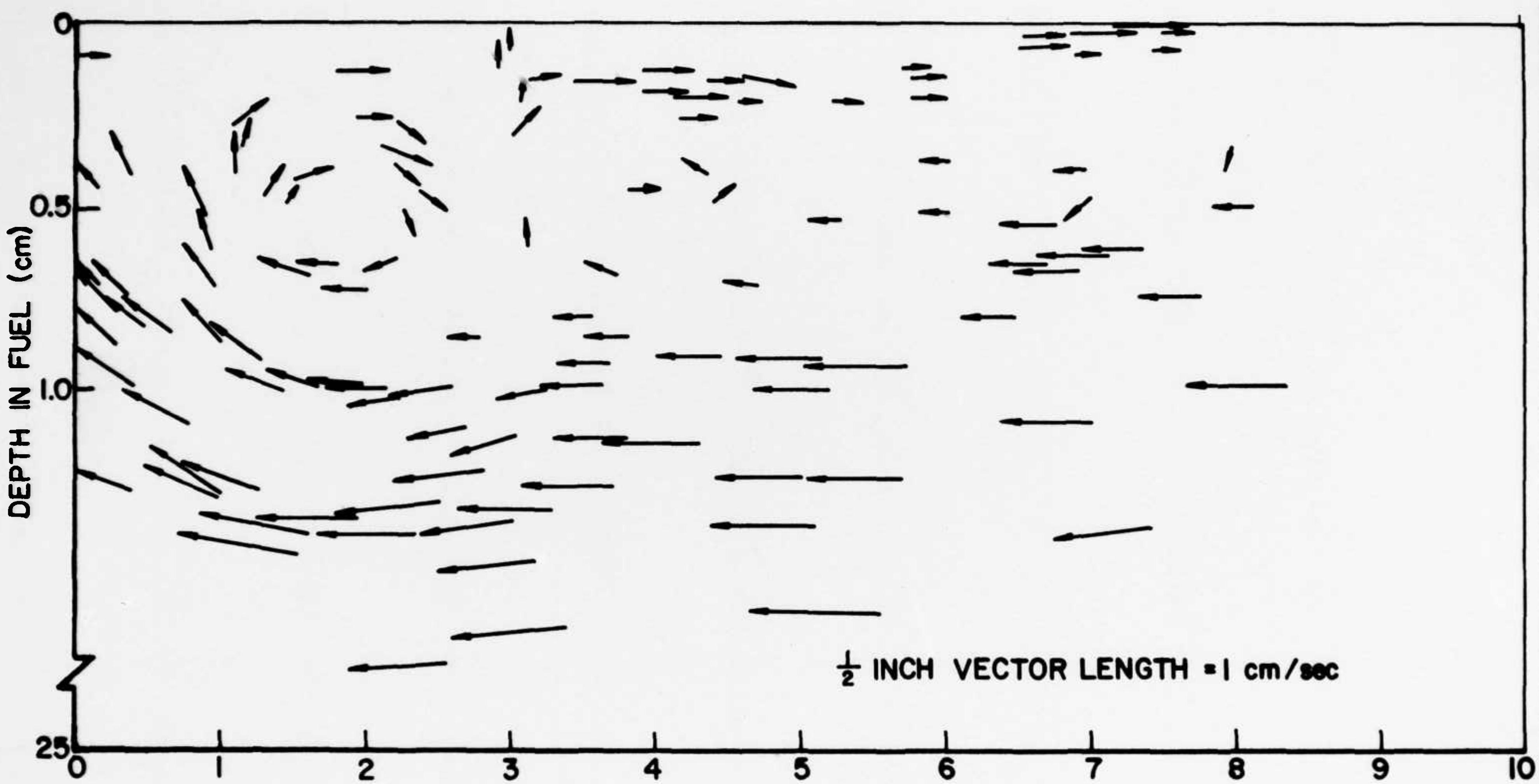
FIGURE 4



FLOW RATE PROBE VOLUME POSITION
△ 90 cm³/sec, 40 cm
○ 170 cm³/sec, 40 cm
□ 180 cm³/sec, 70 cm
CHANNEL HEIGHT (cm)
0
2
4
6
8
0
1.0
2.0
3.0
4.0
VELOCITY (cm/sec)

FIG. 5

6100 088 74



VELOCITY VECTOR FIELD IN SUBSURFACE LIQUID LAYER. FUEL: 45 PERCENT ETHANOL IN DISTILLED WATER. INITIAL BULK TEMPERATURE: 11.5°C FLAME SPEED = 1.65 cm/sec

FIGURE 6

JP13 4409 78

LEGEND: VELOCITY VECTOR FIELD IN SUBSURFACE LIQUID LAYER
45% ETHANOL IN DISTILLED WATER INITIAL BULK
TEMPERATURE = 11.5°C FLAME SPEED = 2.09 cm/sec

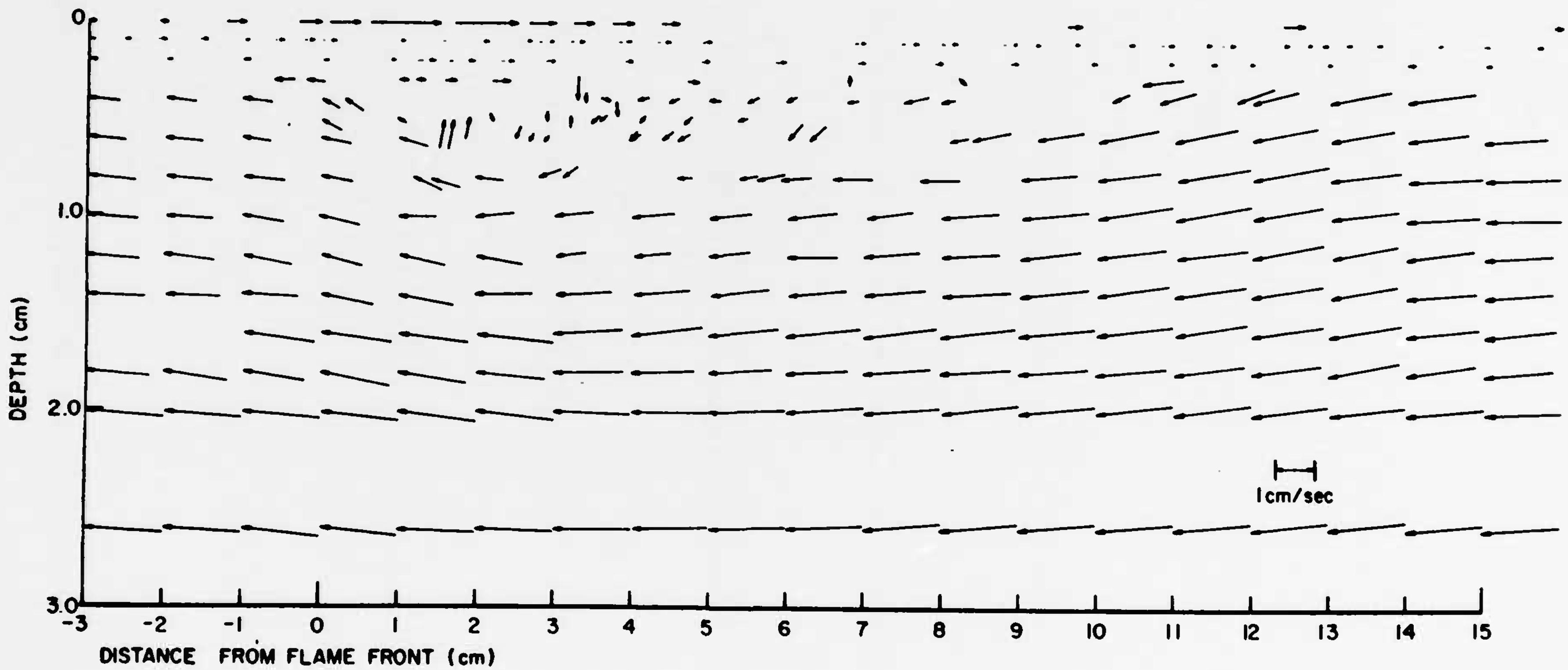


FIG. 7

END

FILMED

9-83

DTIC